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LATITUDINAL COSMIC RAY GRADIENTS AND
THEIR RELATION TO SOLAR ACTIVITY ASYMMETRIES

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Abstract

Data from underground cosmic ray muon telescopes in New Mexico, Bolivia and
Tasmania are shown to be consistent with a latitudinal cosmic ray density
gradient where the cosmic ray density initially decreases with distance
from the neutral sheet and then, farther from the neutral sheet increases
with increasing distance from the sheet on both sides of the sheet.

Introduction. The neutral sheet separates regions of opposite magnetic
polarity in the heliosphere. For much of each solar cycle these regions
are somewhat mis-shapen hemispheres. The sheet is warped, with the
amplitude of the warp varying through a solar cycle, and acts as if it has
its source just above the solar photosphere. Hoeksema et al. (1983)
suggested that 2.5 solar radii is an appropriate altitude.

In a companion paper (Swinson et al., 1990, paper SH 6.2-2, this
conference) we have tried to demonstrate that hemispheric asymmetries in
solar activity, as represented by sunspot numbers, result in the
displacement of the source of the neutral sheet away from the more active
solar hemisphere, thus moving the average position of the neutral sheet in
interplanetary space away from the solar equatorial plane. This in turn
results in the near-earth environment experiencing more days during which
the interplanetary magnetic field (IMF) is directed, for example, towards
the sun (T days) than days during which it is directed away from the sun (A
days). The four possible combinations of solar magnetic polarity and
dominant hemisphere were examined and, for the period 1965 to 1983, our
model correctly predicts the average near-earth IMF polarity. In this
paper we relate this situation to high energy cosmic ray measurements.

Cosmic Ray Density Relative to the Neutral Sheet. Saito and Swinson (1985,
1986), Smith and Thomas (1986) and Webber and Lockwood (1988) have shown
that as the warp of the neutral sheet increases the cosmic ray intensity at
the earth decreases. This can be interpreted to mean that the average
cosmic ray intensity is reduced in periods when the earth is spending more
time well removed from the neutral sheet. A similar conclusion may be
reached from analyses by Newkirk and Fisk (1985) and Badruddin et al.
(1985), who showed that the cosmic ray intensity at the earth is higher at
the time a sector boundary passes the earth than it is on days on either
side. These investigations all utilized neutron monitor data sampling the
cosmic ray regime within 0.1 AU of the earth, and are consistent with a
cosmic ray density or intensity gradient perpendicular to the neutral sheet

with intensity decreasing with distance away from the sheet on both sides in regions relatively close to the sheet.

Cosmic ray detectors having different geomagnetic and detector cutoffs, and looking in various asymptotic directions, permit assessment of the latitudinal gradient at various distances from the earth. Underground muon telescopes have much higher median rigidities than do neutron monitors, and sample the cosmic ray regime considerably further from the earth. If, in addition, their asymptotic directions of viewing are well away from the equator, such telescopes will sample regions of space well removed from the ecliptic and are thus capable of providing information on the latitudinal gradient at distances up to 1 AU.

The latitudinal cosmic ray gradient contributes to the cosmic ray solar diurnal variation. It can be extracted by sorting daily cosmic ray data according to the direction of the IMF, and then obtaining annual average solar diurnal variations for the Toward (T) and Away (A) days separately (Swinson, 1970, 1976; Swinson, Shea and Humble, 1986). The vector difference between the solar diurnal variations for the T and A subsets is an indicator of the resultant perpendicular gradient relative to the earth.

Data. In Figure 1 we show data from the Embudo vertical underground detector in New Mexico (top picture) and solar activity data from the sun's northern and southern hemispheres (bottom picture) from 1965 to 1983 (Koyama, 1985). In the top diagram shading occurs when the A amplitude for the cosmic ray solar diurnal variation exeeds the T amplitude, indicating
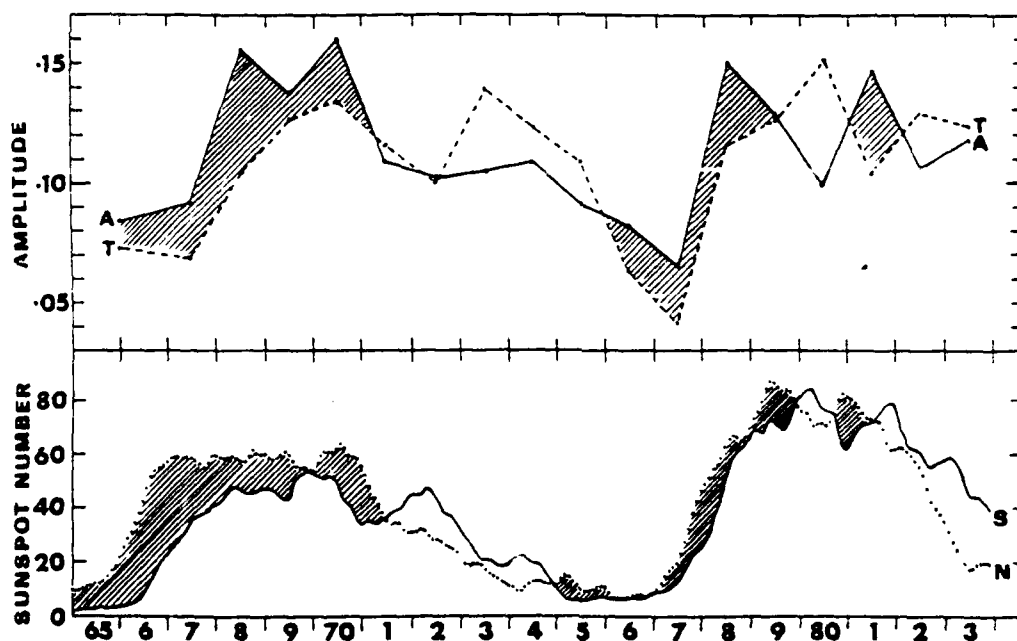

Fig. 1 (Top) Embudo Vertical Telescope: annual amplitudes of the solar diurnal cosmic ray variation for IMF toward (T) and away from (A) the sun; shading occurs when the away amplitude exceeds the toward amplitude. (Bottom) Relative frequency of sunspots on the sun's northern (N) and southern (S) hemispheres; shading occurs when northern sunspots predominate over southern sunspots. The sunspot data are from Koyama [1985].

that the latitudinal cosmic ray gradient seen from the earth points southward (Swinson, 1970, 1976; Swinson and Kananen, 1982; Swinson, Shea and Humble, 1986). The shading (inferring southward gradient) tends to occur at times when excess northern hemisphere solar activity (shown by shading in the bottom picture in Figure 1) occurs.

The Embudo vertical telescope has asymptotic viewing directions close the earth's equator (Regener and Swinson, 1968) and so the cosmic ray data in Figure 1 are representative of conditions closer to the earth. To investigate the cosmic ray regime further above and below the earth we have performed the same analysis on the north, south and vertical telescopes at Embudo and Bolivia and the vertical telescope at Hobart (the data are not shown here due to lack of space). These seven telescopes cover a range of latitudes from about 60°N to 50°S and are therefore sensitive to cosmic ray conditions well above and below the earth's location.

Alternating shaded (inferring southward gradient) and unshaded (inferring northward gradient) regions are present to varying extents in the plots for these seven inclined telescopes in a similar manner to the shaded/unshaded regions shown in Figure 1 for the Embudo Vertical Telescope. In addition to this alternation, it is apparent that there is a greater prevalence of unshaded regions in the results from the more northerly detectors and a greater prevalence of shaded regions in the more southerly data. These observations imply that at significant distances from the neutral sheet the cosmic ray intensity increases again with greater distance from the sheet both north and south of the sheet.

Explanation. Figure 2 shows hypothetical cosmic ray density distributions relative to the neutral sheet for the situations in which the earth is below (left picture) or above (right picture) the neutral sheet. In both pictures the cosmic ray density at the neutral sheet is represented by the number 100, decreasing intensity both above and below the sheet being represented by a purely arbitrary set of numbers which decrease uniformly with distance on each side of the sheet. An indication of the relative density above and below the earth can be obtained by adding together separately the four closest numbers above and below the earth. Doing this reveals that when the earth is below the neutral sheet the average cosmic ray density above the earth is higher than it is below the earth. The reverse situation also applies. A consequence is that a symmetrical gradient perpendicular to the neutral sheet becomes an asymmetrical gradient relative to the earth when the neutral sheet is displaced, on average, away from the solar equatorial plane.

This would account for the alternating occurence of shaded regions and unshaded regions in the top picture of Figure 1, and would apply to a region closer to the earth. However, the predominance of unshaded regions in the results from more northerly detectors and shaded regions in the more southerly data imply that after cosmic ray densities decrease to a minimum at some intermediate distance from the neutral sheet, they start to increase again with distance from the neutral sheet on both sides of the sheet. Detectors whose viewing directions are closer to the earth's equator are more sensitive to the gradients close the neutral sheet, but detectors with viewing directions at higher latitudes also see lateral gradients where density increases with distance from the sheet beyond the intermediate minimum.
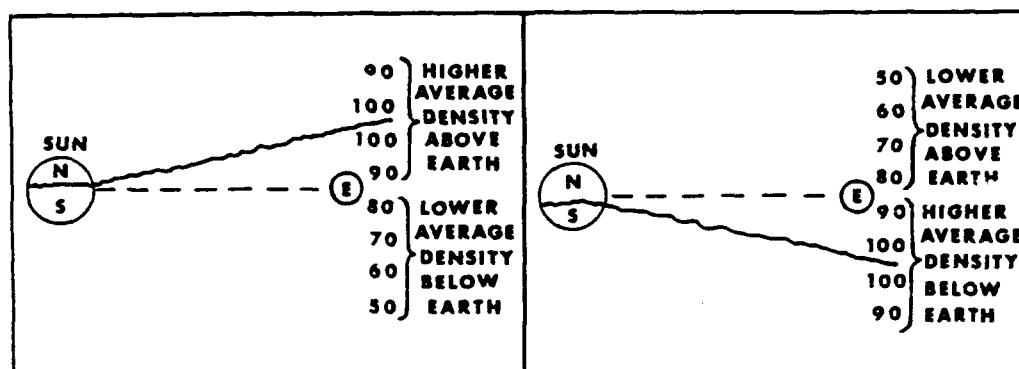
Figure 2. Hypothetical cosmic ray intensities in the region of the earth.

Conclusion. Previously it has been necessary to invoke more complicated mechanisms (Swinson, Shea and Humble, 1986) to account for apparent gradients derived from observations by high energy cosmic ray detectors. From the results presented here it becomes evident that the cosmic ray results are easily accounted for by a symmetrical gradient relative to a neutral sheet whose average location, relative to the earth, changes throughout the solar cycle as solar activity asymmetry changes.

Kota and Jokipii (1983) have calculated that at neutron monitor rigidities the cosmic ray density should decrease away from the neutral sheet on both sides, reach a minimum around 0.25 AU, and then commence to increase with increasing distance from the sheet. Our results, which we note refer to a significantly higher rigidity, and also the neutron monitor results discussed above, are consistent with their prediction.

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